THREE-DIMENSIONAL NUMERICAL SIMULATION OF FLOW AND HEAT TRANSPORT IN A HIGH-TEMPERATURE REACTOR

S. BECKER and E. LAURIEN
Institute for Nuclear Technology and Energy Systems (IKE)
University of Stuttgart, Pfaffenwaldring 31,
D-70550 Stuttgart, Germany

ABSTRACT

In the PBMR with an annular core layout consisting of a central column of graphite pebbles and a surrounding ring of fuel pebbles three-dimensional effects may become important. Hence a new code system based on CFX-4 has been developed and verified by comparison with previous two-dimensional simulations of the HTR-MODUL. As an example of three-dimensional flow and heat transport the influence of an eccentric misplaced package of fuel pebbles in the central column is investigated. A significant influence on the temperature distribution and the maximum temperature is found.

1. Introduction

The correct simulation of flow and heat transport is of great importance for the next generation high temperature gas-cooled reactors (HTR) such as the “Pebble Bed Modular Reactor (PBMR)” [1]. This reactor is currently under development in South Africa on the basis of the HTR-Modul of Siemens/Interatom [2] but with increased thermal and electrical power. In the European High Temperature Reactor Network (HTR-TN) reactors with relatively high power will also be investigated.

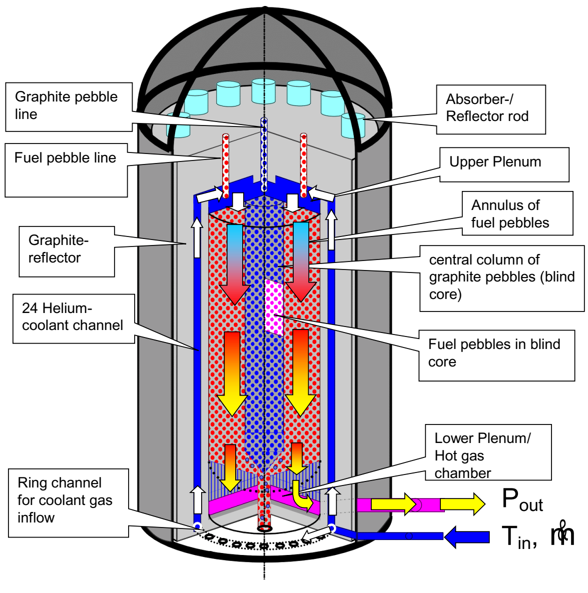

Fig. 1 : Sketch of a HTR with annular core

Higher thermal power than of the HTR-MODUL under the condition of limited maximum core temperature can be obtained by using an annular core consisting of a central column of graphite pebbles with a surrounding ring of fuel pebbles. However, three-dimensional effects of flow and heat transport may arise, e.g. by a package of eccentrically misplaced fuel pebbles in the central graphite column.

Currently only two-dimensional special purpose codes like THERMIX/KONVEK of Forschungszentrum Jülich are available for thermal analysis. Therefore it is necessary to develop three-dimensional (3D) tools.

In this work the already existing code CFX-4 for three-dimensional flow analysis from AEA Technology [3] has been employed. The necessary models for pebble beds and the corresponding flow and heat transport phenomena have been implemented.

The new code has been validated for several steady state and transient high-temperature experiments for Helium and Nitrogen flow in a pebble bed conducted at the SANA (**S**elbsttätige **A**bfuhr von **Na**chwärme) test rig of Forschungszentrum Jülich, Germany [4]. In the experiments the heat transport has been investigated for a simplified model of a

HTR-MODUL 3-4 hours after reactor shutdown. The simulations have shown good agreement to the experimental results for both gases [5].

In this paper preliminary 3D results of the new code for a simplified model of the South-African PBMR as of 2000 with 270 MW thermal power are discussed. Steady simulation results show the influence of a package of eccentrically misplaced fuel pebbles in the central column on the maximum temperature for (i) short time after injection and for (ii) an instant shortly before release of the fuel pebbles.

In order to demonstrate that the unsteady results of the new code agree with the two-dimensional simulation results of THERMIX/KONVEK unsteady 3D-simulations of the HTR-MODUL (HTR-200) have been performed. Results are presented for a loss-of-forced-coolant accident at nominal pressure and with fast depressurisation.

2. Mathematical Model

The flow and heat transport in a High-Temperature Reactor is simulated unsteadily by the Heterogeneous Model, consisting of two sets of equations for both media, the gas, eqs. (1)-(3), and the pebble bed together with the solid parts, eq. (5). The volume porosity φ is used to determine, whether a single phase gas flow (φ=1), flow and heat transport through the pebble bed (0<φ<1) or heat transport in the solid parts (φ=0) are simulated. The heat transport in the pebble bed and the solid parts of the reactor like the side reflector are described by a temperature equation. The interaction of both media, gas and pebble bed, is modelled by interaction terms for pressure drop B_j, eq. (4), and heat exchange $\dot{q}'''$.

The gas flow in the upper plenum, the coolant channels and the pebble bed are described by the three-dimensional spatially averaged conservation equations for flow through a porous medium as given below

$$\frac{\partial \varphi \rho}{\partial t} + \frac{\partial \varphi \rho u_i}{\partial x_i} = 0 \tag{1}$$

$$\left(\frac{\partial \varphi \rho u_j}{\partial t} + u_i \frac{\partial \rho \varphi u_j}{\partial x_i} \right) = B_j - \varphi \frac{\partial p}{\partial x_j} + \varphi \frac{\partial}{\partial x_i} \left(\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right) + \varphi \rho g_j \tag{2}$$

$$\frac{\partial \varphi \rho h}{\partial t} + \varphi \frac{\partial \rho u_i h}{\partial x_i} = \varphi \frac{\partial}{\partial x_i} \left(\frac{\lambda}{c_p} \frac{\partial h}{\partial x_i} \right) + \dot{q}''' \tag{3}$$

with fluid density ρ, velocity u, static pressure p, viscosity μ, enthalpy $h=c_p*(T-T_{ref})$, heat conductivity λ, heat capacity c_p, volumetric exchange heat flux $\dot{q}''' = \alpha(T_{POR} - T)$ between pebbles and gas, the volume porosity φ and the additional body force B_j in j-direction due to additional flow resistance caused by the pebble bed, modelled by Ergun's law

$$B_j = -\frac{150\mu(1-\varphi)^2}{d_P^2 \varphi^3} u_j - \frac{1.75\rho(1-\varphi)}{d_P \varphi^3} |u| \cdot u_j \tag{4}$$

with the diameter d_P=0.06m of the pebbles.

The pebble bed and the solid parts are described by the continuous porous medium approach and the heat transport is modelled by

$$(1-\varphi)(\rho c)_{por} \frac{\partial T_{Por}}{\partial t} - (1-\varphi)\lambda_{eff} \frac{\partial^2 T_{Por}}{\partial x_i^2} = \dot{q}_N''' - \dot{q}''' \tag{5}$$

with T_{Por} as the temperature of the pebble bed, the exchanged volumetric heat flux $\dot{q}'''$ between pebble bed and gas, the volumetric nuclear heat production $\dot{q}_N'''$ and the effective heat conductivity λ_{eff} of the porous medium including a model for radiation described by the correlation of Zehner and Schluender [6]. The variation of porosity near the walls is modelled by the correlation of Cheng and Hsu [7] resulting in a 50% higher maximum porosity than in the interior (φ_∞=0.4). The heat transfer from the porous medium to the fluid is described by a volumetric heat transfer coefficient α in accordance to

KTA-rule 3102.2. Thermal dispersion effects due to additional mixing of gas in the core is taken into account by a model of Bauer [8] by increasing λ.

3. Numerical Method

The set of equations given above is integrated in space and time by the finite-volume CFD-code CFX-4 for steady state and transient cases. The equations have been solved using the SIMPLEC-algorithm. The solid parts in the reactor model are described as conducting solids and are solved accordingly. All necessary models have been implemented by the USER-FORTRAN interface. The transient cases have been solved by a second-order accurate backward difference implicit time stepping method. The time step width was chosen to resolve the initially steep gradients of the decay heat curve.

4. Results

The three-dimensional reactor models of the HTR-MODUL (HTR-200) and the PBMR (PBMR-270) are shown in fig. 2 with the initially given power distribution. For the HTR-MODUL the power distribution was taken from THERMIX/KONVEK coming from neutronic Monte-Carlo-calculations with ORIGEN. For the PBMR an axisymmetric power distribution with given total thermal power was assumed to have a distribution similar to the HTR-MODUL but with no power production in the central column. To simulate the effect of misplaced fuel pebbles an eccentric power-generating section in form of a quarter cylinder with 1 m height as shown in fig. 2 right is used, resulting in a total power of 280 MW.

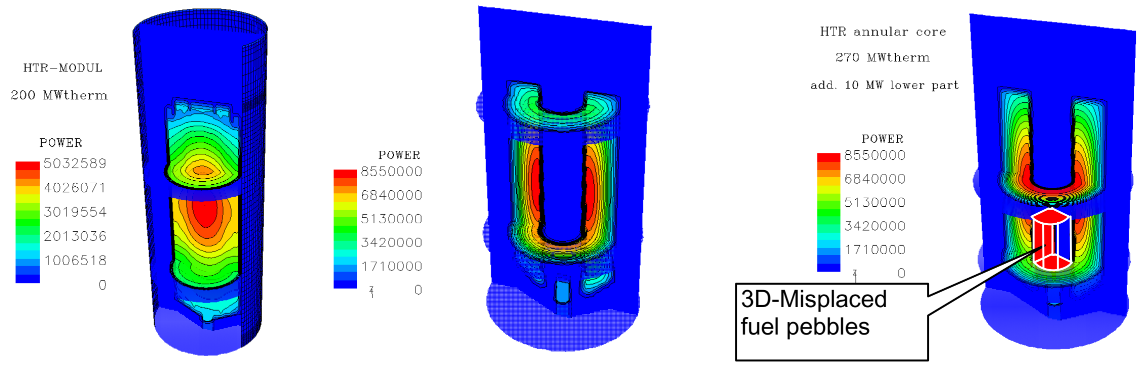

Fig. 2. Model of HTR-200 (left) and of the PBMR-270 (middle: nominal power, right: with additional fuel pebble package in the lower part of the core)

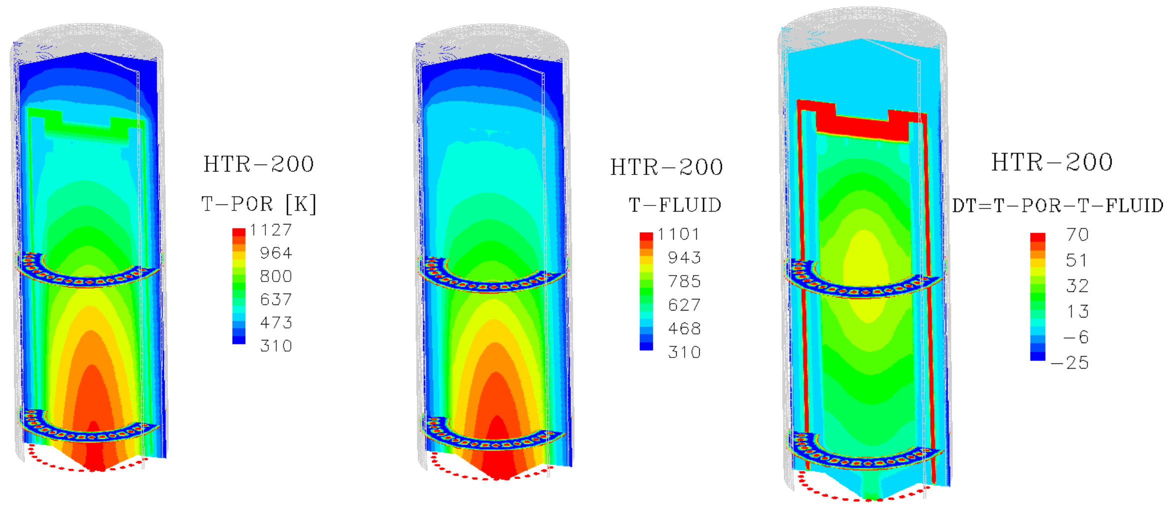

Fig. 3 : HTR-200 - Distribution of temperature in the solid part and pebble bed (left), fluid (middle) and the temperature difference between pebble bed and fluid (right)

First, the operational state of the reactor has been simulated as a basis for later transient accident simulations. The simulation results for the operational state of the HTR-MODUL with 200MW thermal power and a mass flux of 80 kg/s at 250°C is given in fig. 3 with the distribution of the temperature in the pebble bed (left), in the gas (middle) and the temperature difference $dT=T_{Por}-T$ (right). The pressure drop due to the core of 0.6 bar was in good agreement to documented data. The maximum temperature of 1130 K agrees well with 1139 K from THERMIX/KONVEK.

As an initial condition for the unsteady cases of the PBMR-270 a steady simulation with 126 kg/s inlet mass flux of Helium at 500°C was performed. The symmetric case at nominal power of 270 MW_{therm} is shown in fig. 4 left. A maximum temperature of around 1230K has been calculated. In case the misplaced fuel pebble package is located in the upper part of the core, which corresponds to an instant shortly after injection, we have calculated an increase in the maximum temperature of 20K compared to the standard operational case. The maximum temperature is almost not affected if the additional fuel pebbles are in the lower part of the reactor core, which corresponds to a later time shortly before the pebbles will be taken out of the reactor core.

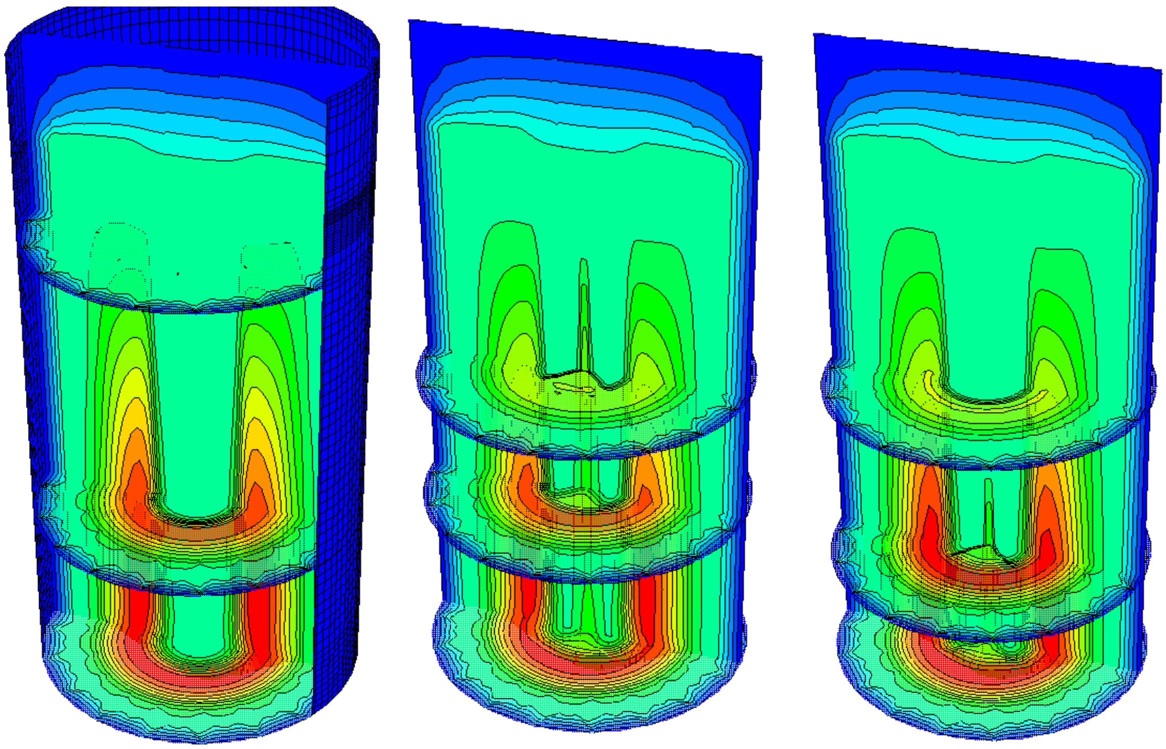

Fig. 4. Temperature distribution in the solid part and pebble bed of the PBMR-270 (left: nominal configuration, middle : with misplaced fuel pebble package in the upper part, right: misplaced fuel pebble package in the lower part)

Next, preliminary unsteady results for the HTR-200 are presented for the pressurised loss-of-forced-coolant-accident which has been simulated on the basis of the operational state. Here the reactor is suddenly shut down by inserting all control rods and stop of forced cooling. Heat can only be transferred by natural convection, heat conduction and radiation. The maximum temperature in the pebble bed at the locally fixed point of maximum temperature is shown in fig. 5 together with data achieved by THERMIX/KONVEK. As can be deducted from fig. 5 the results agree well with previous results from THERMIX/KONVEK taken from the reactor safety analysis report of the HTR-MODUL of 1988 [9]. The deviation is around 20K which is within the standard deviation of the results due to the accuracy of the models used.

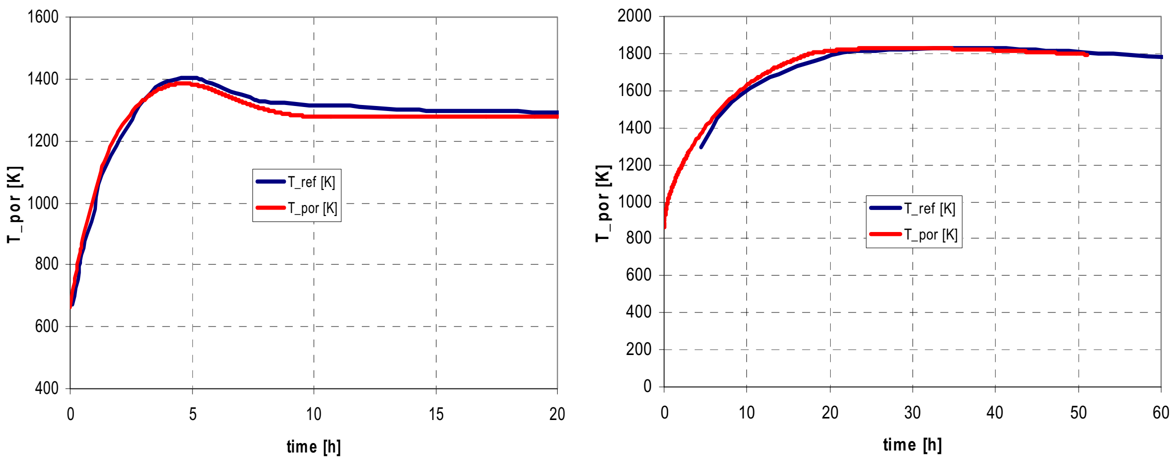

Fig. 5. Temperature in the pebble bed T_por at the point of maximum temperature of the HTR-MODUL for passive decay heat removal at nominal pressure (left) or with fast depressurisation to 1 bar (right) compared to previous results T_ref from [9] (reference data : black line; calculated data : grey/red)

5. Conclusions and Outlook

It has been shown that the CFD-code CFX-4 with our extensions predicts the three-dimensional heat transfer in modular HTRs well. The time-dependent temperatures in the reactor have been simulated accurately for the HTR-MODUL of Siemens/Interatom. These simulations are only possible on supercomputers. The preliminary steady simulations of three-dimensional effects for the PBMR have shown the influence of non-symmetric power distributions on the temperature distribution and the maximum temperature in the reactor.

Unsteady three-dimensional simulations are possible and will be performed for the PBMR.

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